

ABSTRACT

A global ocean data assimilation system producing routine, near real-time, physically consistent analyses has been established, so as to help monitor ocean circulation and to better understand processes underlying seasonal-to-interannual changes. The system is a product of the consortium, "Estimating the Circulation and Climate of the Ocean" (ECCO). Analyses are regularly updated and are available via a Live Access Server at <http://www.ecco-group.org/las>. The modeling and assimilation systems are summarized and aspects of the products and their applications are highlighted.

Model

The MITgcm is employed in a near-global domain (78°S–78°N). Model resolution is 1° horizontally, "telescoping" to 0.3° latitudinally within 10° of the equator, and 10m vertically within 150m of the surface. (Total grid dimension is 360×224×46 = 4×10⁶.) The GM isentropic mixing scheme and the KPP mixed-layer formulation are employed. The model is forced by NCEP products (time-mean replaced with those of COADS) with relaxation of temperature and salinity at the sea surface towards observed values.

Assimilation System

A sequence of assimilation methods is employed (Table 1); **Green's functions** (GF) [8], **partitioned Kalman filter** and **RTS smoother** (PKF and PS; Fig 1) [2], **adjoint method**. The approach takes advantage of the respective methods' fidelity and computational efficiency. All three methods estimate both the model state and the source of model errors (controls), resulting in a physically consistent evolution of the model estimate (Figs 2 & 3). The analyses are updated periodically and are available at ECCO web sites (Fig 4).

	Control	d.o.f.	Data Assimilated	period
GF	mixing coefficients, initial TS, mean forcing	17	temperature (XBT, PALACE, WOCE, TAO, HOTS, BATS)	1993-2000
PKF/PS	time-varying wind forcing (wind and heat flux), initial TS	10 ⁷	TOPEX/Poseidon (Jason-1) XBT, WOCE, TAO	1993-present
Adjoint		10 ⁷	TOPEX/Poseidon, Levitus TS	1997-2001

Table 1: ECCO Routine, Near Real-Time Assimilation System

The hierarchy of data assimilation methods allows estimation of different elements of the model uncertainties in a computationally efficient manner.

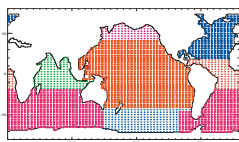


Fig 1: Partitioning Employed in the ECCO Kalman filter and smoother. Estimation is carried out separately in different overlapping regions. The smaller dimension of each separate partition allows for dramatic computational savings [2].

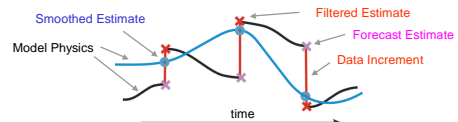


Fig 2: Schematic of Model State Evolution (e.g., Temperature). Data increments (red line) correct the consequence of model errors, but do not correct the source of errors. The red updates are inverted in the blue smoothed estimate, that explicitly corrects the state and model error sources (controls). The result (blue curve), in contrast to the red estimate, has a temporal evolution that can be accounted for physically.

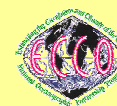
"Seasonal-to-Interannual Variability of the Ocean During WOCE, Estimated by the ECCO Routine Global Ocean Data Assimilation System"

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Physical Consistency

Temporal evolution of most data assimilated solutions are not physically consistent; e.g., changes in energy and mass cannot be fully accounted for (Fig 2). The solution to this problem is to invert data increments so as to correct the source of model errors in addition to the model state.

Mathematically, data assimilation can be identified as an inverse problem of solving a set of simultaneous equations for the model state (vector x) and model errors (control vector u), as a function of time, given observations (vector y) and the theoretical relationships among the elements (H , A , G) (Eq 1).

$$\begin{matrix} \text{Observations} & \begin{matrix} \rightarrow \\ \rightarrow \\ \rightarrow \end{matrix} & \begin{matrix} Hx \\ y \\ y \end{matrix} \\ \text{Model Eqs} & \begin{matrix} \rightarrow \\ \rightarrow \\ \rightarrow \end{matrix} & \begin{matrix} x - Ax_{t-1} - Gu_{t-1} \\ 0 \\ 0 \end{matrix} \end{matrix} \quad \begin{matrix} x: \text{model state} \\ y: \text{observations} \\ H: \text{observation operator} \\ A, G: \text{model dynamics} \\ u: \text{control (e.g., forcing, and model errors)} \end{matrix} \quad (1)$$

Kalman filtering and other sequential assimilation methods are inversions of only the observations. In comparison, smoothing (RTS smoother, adjoint method) also inverts the model equations, explicitly solving for state and controls yielding a solution whose temporal evolution is physically consistent. (This requires that the model of the control, G , is explicitly identified and that it is physically sensible.)

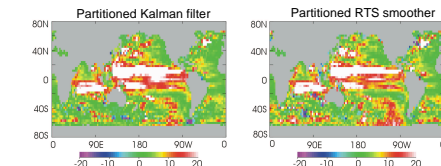


Fig 3: Explained TP Variance Relative to Simulation, Averaged in Time The assimilation improves the skill of the model nearly universally; 47% and 46% of T/P variance is explained by PKF (left) and PS (right), respectively, relative to 29% for the simulation. The relative skill is defined as TP-simulation residual variance minus that of TP-assimilation. Units are in cm². PS solution here is model simulation forced by smoothed wind estimates. Similarities of the PS solution to the PKF solution demonstrate the goodness of the smoother inversion. See [9] for further analysis of smoothed wind.

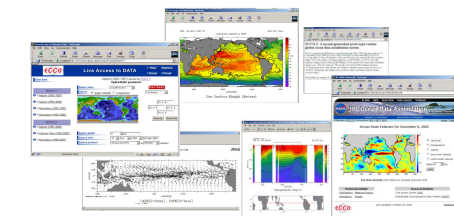


Fig 4: ECCO Live Access Server at <http://www.ecco-group.org/las> ECCO products are updated regularly and are available via the Live Access Server (LAS) at <http://www.ecco-group.org/las>. Latest estimates are highlighted at <http://ecco.jpl.nasa.gov/external>.

Results and Applications

ECCO products have a reasonable skill in resolving many aspects of the ocean's circulation, including hydrographic structures and its variabilities (Figs 6, 7, 8). The estimates provide a complete description of the circulation, that facilitates analyses of ocean processes and their effects. For instance, its consistency permits closing budgets of mass [3, 7] and heat [5], allowing investigations into the mechanisms of ocean circulation [3, 6]. The data assimilated solutions are generally more accurate than those of the unconstrained model, permitting better estimation of the effects of the changing ocean circulation. Recent geodetic applications provide novel integrated measures of ocean circulation that also demonstrate the fidelity of the data assimilation (Figs 9, 10).

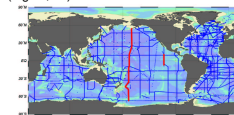


Fig 6: Location of Hydrographic Sections in Figs 7 & 8 (red). Model equivalent of WOCE sections as in Figs 7 & 8 are available at www.ecco-group.org.

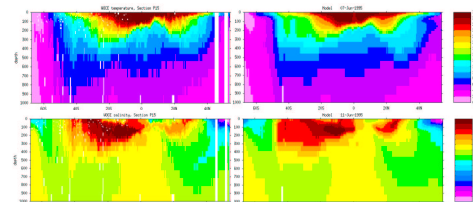


Fig 7: Temperature (top) & Salinity (bottom) Sections: P15 (170°W) (Left) WOCE, (Right) ECCO estimate for 7 June 1995.

The ECCO model reasonably resolves many aspects of the mean hydrographic structures, such as the strength and position of the thermocline and its variations, and the distribution of different mode waters (e.g., AAW, NPTW).

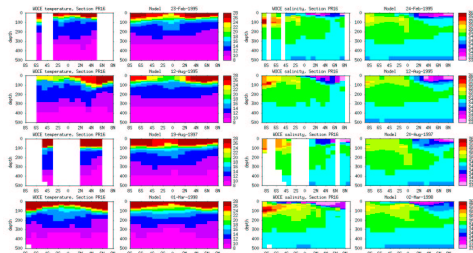


Fig 8: Repeat Temperature (left) & Salinity (right) Sections: PR16 (110°W) ECCO estimates resolve many of the observed seasonal-to-interannual changes in hydrographic structure. The model effectively interpolates/extrapolates over data void regions. Together with its physical consistency, the estimates provide a complete description of the circulation.

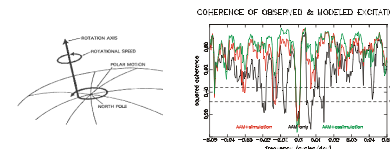


Fig 9: Polar Motion [4] Observed polar motion excitation is most coherent with ocean-atmosphere estimates based on ECCO assimilation (green) than either atmosphere alone (black) or without ocean data assimilation (red). Left panel shows schematic of Polar Motion.

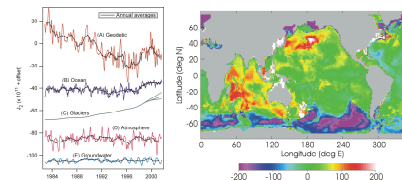


Fig 10: Earth Dynamic Oblateness (J2) Variations [1]. The recent non-linear change in J2 (the degree 2, order 0 spherical component of the gravity field) can largely be ascribed to changes in the ocean (15% increase in residual linearity by ECCO estimate) and changes in sub-polar glaciers (21% (left). [Ocean simulation accounts for an 11% increase.] The rapid 1998 change in the ocean is due to a shift in column integrated mass from the Southern Ocean to the Pacific and Indian Oceans (right; 1999-2000 minus 1996-1997; N/m²).

Conclusion

A routine, near real-time, global-ocean, data assimilation system has been established. The assimilation system assimilates satellite sea level observations (TOPEX/Poseidon, Jason-1) and hydrographic temperature data (XBTs, ARGO, WOCE, etc), using a high-resolution global ocean general circulation model. Planned future upgrades include incorporation of additional observation types, expansion of the control space, and migration to a higher resolution model (1/4°).

The ECCO near real-time state estimates are available at 10-day intervals (12-hours for sea level and bottom pressure, daily for optimized surface forcing) via the Live Access Server at <http://www.ecco-group.org/las>. The estimates are characterized by their optimality (e.g., nearly universal improvement over unconstrained model) and physical consistency (e.g., closed heat and tracer budgets). Results are being used in studies of the ocean's heat balance and of mechanisms of interannual changes. Products are also being applied in studies of biogeochemical cycle and geodesy. We invite additional analyses and applications of these estimates.

References

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